The Modular Neutron Array (MoNA) is a large area detector consisting of 144 plastic scintillating bars housed at the National Superconducting Cyclotron Laboratory (NSCL). Used in conjunction with a 4 T sweeper magnet, it is a high-efficiency neutron detector for studying nuclei near or past the neutron dripline. First experiments concentrated on the study of nuclei decaying by single neutron emission. However, future experiments are planned to explore for example the decay of $^{13}$Li into $^{11}$Li and two neutrons. Thus it will be necessary to distinguish one-neutron hits from two-neutron hits in MoNA. Data from experiments on the decay of $^{25}$O into $^{23}$O and a neutron and the population of unbound states from direct fragmentation at the NSCL were used to develop code that sorts the time ordering of events, and to show that recoil protons do not show up in secondary hit spectra contrary to what was expected.
Introduction

The Modular Neutron Array (MoNA) is a highly efficient large-area neutron detector housed at the National Superconducting Cyclotron Laboratory (NSCL). This paper will discuss the design, calibration, and functioning of MoNA, an experiment with $^{25}\text{O}$, and the process of tracking neutrons through the detector.

Purpose

MoNA’s primary purpose is for measuring properties of isotopes near the neutron-drip-line. This is the line on the periodic table of the isotopes beyond which nuclei “drip” off neutrons on the order of $10^{-22}$ s or less. These are neutron-unbound states. A more rigorous definition is shown below.

$$S_n = E_B(Z, N) - E_B(Z, N - 1) = 0$$

This equation can be stated as: the neutron separation energy equals the difference in binding energies between the N neutron isotope and the N-1 neutron isotope, which also equals zero, [1]. It does not take any energy to strip a neutron from the N neutron isotope.

These states are interesting because they exhibit properties not normally found in stable nuclei. The existence of halo-nuclei, with nucleons found outside of the nucleus is one such example. Also, many astrophysical processes produce nuclei in these states.

The Coupled Cyclotron Facilities of the NSCL make measurements of these states possible. This is accomplished by collisions of rare isotope beams with targets at relativistic speeds. Reaction products must then be studied to understand specifics of the reaction. MoNA also has a use training undergraduate students in experimental physics.

Experiments with MoNA

Experiments start with a beam delivered by the coupled cyclotrons. This beam hits a primary target and possibly a secondary target using fragmentation and separation techniques. After the target, there are many reaction products—charged particles and neutrons. This means that charged particles must be “swept” out of the reaction products before they reach the detector. The 4 Tesla sweeper magnet designed and built at the National High Magnetic Field Laboratory at Florida State University does this. Measurement of the charged particles allows the energy of the neutrons to be determined.

![MoNA setup](image.png)

**Figure 1** – MoNA setup. The beam comes in from the left. The sweeper magnet sends the charged particles into the detectors. MoNA is positioned straight ahead, and can be
placed closer to the sweeper magnet for greater statistics, or further back for better position resolution.

The MoNA detector is composed of 144 plastic scintillating bars stacked in 9 layers of 16. The scintillation material is Bicron BC-408. The bars can be re-configured depending on the experiment’s needs. For instance, they could be stacked in 12 layers with 12 bars each. Each bar has a photomultiplier tube on either end. These tubes are used to turn light produced in the bar into an electronic signal, which the data console then decides whether to record or not. The current MoNA configuration is shown in Figure 2 below.

![MoNA Detector](image)

**Figure 2** – The MoNA detector as currently arranged. The passive steel converters are not currently in place.

When a neutron hits a molecule in the bar, a recoil proton may be released. The scintillating material then releases two photons as the charge moves through it. The photons travel in opposite directions through the bar. PMTs then detect the light and produce an analog electronic signal. The height and depth of the hit is determined by which bar registers. The position in the bar is found by measuring the mean times for the two photons.

The signal from the PMTs goes to a charge to digital converter (QDC) that measures the amount of charge in the signal. It’s also sent to a constant fractional discriminator (CFD). This filters out improper signals and produces a digital signal. The signal is then sent to a time to digital converter (TDC), which measures the arrival time, then to a mean timer that finds the mean of the signals from the two different phototubes, [2]. The basic electronics set up is shown below in Figure 3.
The modules alone have a mass of 3550 kg, so a support structure was built that allows MoNA to be moved, albeit slowly, by the NSCL’s 40 ton crane. A movement of about three meters in July 2005 took about 2 hours. The reason for the slow movement is that with 144 bars comes 288 PMTs, which each have 3 cables. This amounts to 864 cables just from the bars. Connections to outside computers and other timing detectors down the beam line add more. The detector has to be moved a little, then the control module, then the detector and so on. The new position gives MoNA a better resolution for the study of the population of unbound states from direct fragmentation. The placement of MoNA in the NSCL is shown below in Figure 4. Because N6 has an open back end, neutron-blocking walls that are normally used to close the N4 vault are moved behind MoNA to close the area off for experiments.

**Figure 3 – A simple electronics schematic of MoNA.**

**Figure 4 – the CCF.**

**Calibration**

Although MoNA is generally used with the sweeper magnet, it is not always necessary to do so. Sometimes a calibration run with cosmic rays is needed. The cosmic rays are well studied, so this makes it possible to do high voltage gain matching, x-
position calibration, and timing calibration. The PMTs must be gain matched in such a way as to guarantee uniform detection efficiency across the bar. If one tube is more sensitive than the other and weak photons are created near the stronger PMT, light attenuation may prevent the other from being measured. The mean time data must be transformed into x-position to find the energy of the neutrons. The timing calibration is done by finding the difference between when the PMTs fired and when they should have fired.

When the PMTs should have fired is known because the velocity of the cosmic rays and the distance between bars is known very well. When cosmic rays that are moving straight down are gated, each signal should occur about 0.344 s after the previous. This can be found from the simple formula

$$t = \frac{d}{v}$$

where $t$ is the expected time difference between bars, $d$ is the distance from the center of one bar to the next, and $v$ is the velocity of cosmic rays. The values are $d = 10.26 \pm 0.01$ cm, and $v = 29.8$ cm/ns. Putting the expected time difference minus the measured time difference into an “offset” file completes the calibration.

There is an offset for every bar in the array measured relative to bar A8. This is the first module the beam line passes through. The calculated time to go from bar A8 to bar A0 is 2.34 ns. The measured time is found by finding the centroid of the peak between the dashed lines. It is equal to 2.83 ns. The offset would then be -0.49 ns. In other words, the A0 bar should be firing 0.49 ns faster than it does. Cosmic ray data taken during a MoNA experiment on the population of neutron-unbound states from direct fragmentation in early August 2005 was used. Figure 5 below shows a histogram of the difference in average time for the bars A0 and A8.
Figure 5 – Histogram of mean time of A0 minus mean time of A8. The offset is found by subtracting this from the theoretical time. The dashed lines indicate the peak of interest.

Tracking Neutron Events

In future experiments, it will be necessary to discern one neutron events from two neutron events. This is because experiments are planned that involve nuclei that can decay into $N - 1$ nuclei plus a neutron or $N - 2$ nuclei plus two neutrons. The experiment must discriminate between one neutron hitting twice and two neutrons hitting once.

With this motivation, it was decided that a code must be written that sorts the hits of an event properly. This can be done using the Spectcl spectra analyzing program and Tcl programming language. Tcl (Tool Command Language) is UNIX shell language that allows the user to automate routine chores, [3]. The basic idea is to make a list of which numbered hit the detection could be, and then as data comes in, to place each hit into its corresponding element. When Andrew Ratkiewicz (Indiana University South Bend) first completed this code, it was found that about 75% of the original sorting code had placed the hits into the wrong spectra. It was decided that this code could then be used to find out more about how recoil protons travel through the detector.

As a recoil proton is traveling through the bar, there is a possibility it could travel into another bar, thereby causing detection in a bar that did not have a neutron event. The hypothesis is that the second hit would then actually be the proton, whereas the third would be the neutron. By looking at events that stayed in one layer and either traveled up or down, we can discern more about this incident.

First, I used the sorting code to find the distance between a specific hit and the first one. Only the first four hits are needed. This was gated on the neutron peak in the time of flight for the first hit spectrum. This is to assure that we are looking at neutron events and not background.

The $x$, $y$, and $z$ coordinate convention used is with positive $z$ in the direction of the motion of the beam, positive $y$ up, and positive $x$ to the left of the beam. This is shown in Figure 6 below. Then by gating on hits that are up or down one bar and whose delta-$z$ is 0, we can look at hits that only happen in one layer. Data from the early August experiment on population of unbound states from direct fragmentation was used.
Figure 6 – Coordinate configuration of MoNA.

To make the results more clear, the data is presented below in Figure 7 with analysis to follow.

Figure 7 – The left column is gated just on the neutron peak, while the other two are gated on the bar above and below respectively.

By following either just the up or down moving hits, a proton can be distinguished by noticing it should moving in the opposite direction in the center of mass frame to conserve momentum. This would imply that the second delta-y is anti-correlated with the third. However, the data shows that the two are correlated. This implies that the second hit is not a recoil proton, but the same neutron.

It was observed during this analysis that there were peaks on the positive side of the delta-z hit one minus hit two spectrum. This is shown in Figure 8 below. This was not expected, as the beam comes from the negative side of the z-axis, and so it seems delta-z should be negative with the delta convention. I hypothesized that the extra peaks were backscatter.
Figure 8 – This shows the positive delta-z values. Because the beam is traveling into the detector, negative values would be assumed.

In order to test this, I wrote another code that gated on the first layer. This would mean that backscattered neutrons would leave the detector, and so we would not expect to see the peaks. The gate is shown in Figure 9, and the result in Figure 10 below.
Figure 9 – Sorted z first hit spectrum. A gate was placed on the first peak in this spectrum to only include those first hits that happened in the first bar.

![Sorted z first hit spectrum](image)

Figure 10 – Delta-z for hit 1 minus hit 2. This has been gated on the first layer in the detector and hence backscatter would be out of the detector.

As hypothesized, the positive peaks vanish. This refutes the original hypothesis. One uncertainty about this data is that it seemed the number of counts in different spectra was not always coherent. When a spectrum is gated, there should be fewer hits analyzed then in the original un-gated spectrum. Although the effect was small, this was not always the case.

Conclusion

The MoNA detector is a useful tool for studying physics near the neutron drip-line. It was used to show that contrary to what was believed, recoil protons do not show up in secondary hit spectra, and hence it is the incoming neutron being measured, not a proton. Further analysis should be done to find what the source of the gated spectra anomaly was, even though the effect was small.
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References


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